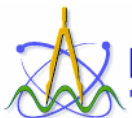


Problems and Issues for Ion Trap QC by Carl J. Williams National Institute of Standards & Technology

Sponsors



<http://qubit.nist.gov>



NIST Physics Laboratory

NIST Boulder Ion Trap Meeting
February 21, 2006

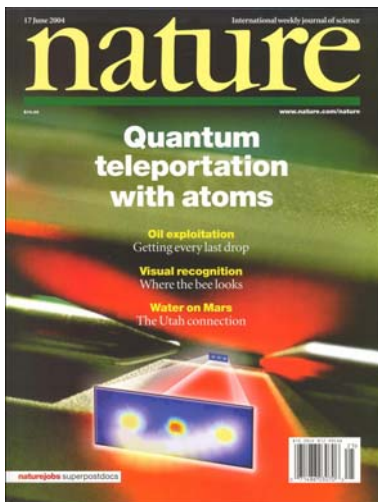
NIST

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Most Advanced Quantum Computing Effort

Ion trap quantum computing is considered to be one the most advanced efforts in the world:

- **Passes all of the DiVincenzo Criteria for Scalability**
 - a) Well characterized, scalable qubits
 - b) Ability (re)initiate to a starting state
 - c) Decoherence times longer than operation time
 - d) A universal set of one- and two-qubit gates
 - e) State specific readout
 - f) Efforts toward photon-ion coupling showing promise



- Teleportation of quantum state of an ion
- Separation & movement of entangled ions
- Quantum error correction demonstrated
- Quantum dense coding
- Quantum Fourier transform ran
- Demonstration of quantum logic clock
- 8-qubits entangled, 6-qubit GHZ state

The DiVincenzo Criteria (5+2)

- ❑ Scalable Physical System with well Characterized Qubits
- ❑ Initialization of Qubits to a Simple Fiducial State
- ❑ Long Decoherence Time: $t_{\text{decoherence}} \gg t_{\text{gate}}$
- ❑ Universal Set of Quantum Gates \Rightarrow Entanglement $|000\dots\rangle$
 - Arbitrary One Qubit Operations
 - Almost any two Qubit Gate – *e.g.* Controlled-Not or Phase Gate
- ❑ A Qubit Specific Quantum Measurement – Readout

Two Additional Criteria for Network Compatibility

- ❑ Ability to Interconvert Stationary and Flying Qubits
- ❑ Ability to Transmit Flying Qubits between two Locations

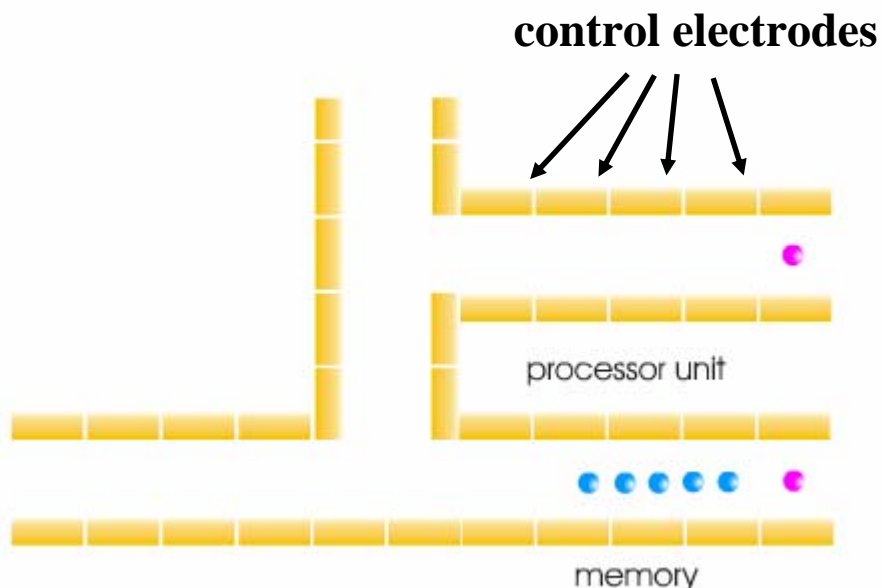
Hidden within these criteria is the need to interact any two arbitrary qubits and to do so in parallel. This is essential for error correction and scalability.



The Question of the Day

- What do I need, technically and experimentally to move from 8 qubits to 20-100 qubits?
- Is this the right number?
- What technical solutions – *e.g.* blue lasers, new traps, better detectors, ... -- will make this more likely
- What basic parameters will help those creating simulations to better guide us through the complex space?
- Should we select a ion?
- Is it time to further optimize the gates?
- What does the ion trap real estate look like and how much does it cost?

Multiplexed Ion Trap Architecture



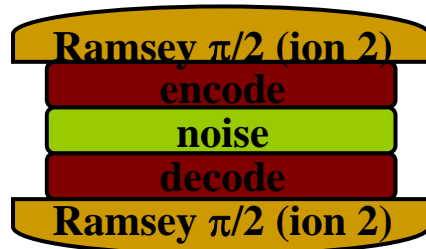
- Interconnected multi-trap structure
- Route ions by controlling electrode potentials
- Processor sympathetically cooled
- No individual optical addressing during two-qubit gates (can do gates in strong trap \Rightarrow fast)
- One-qubit gates in subtrap
- Readout in subtrap

- Wineland *et al.*, *J. Res. NIST*. 103, 259 (1998).
- Kielpinski, Monroe, Wineland, *Nature* 417, 709 (2002).
- Other proposals: DeVoe, *Phys. Rev. A* 58, 910 (1998).
- Cirac and Zoller, *Nature* 404, 579 (2000) .

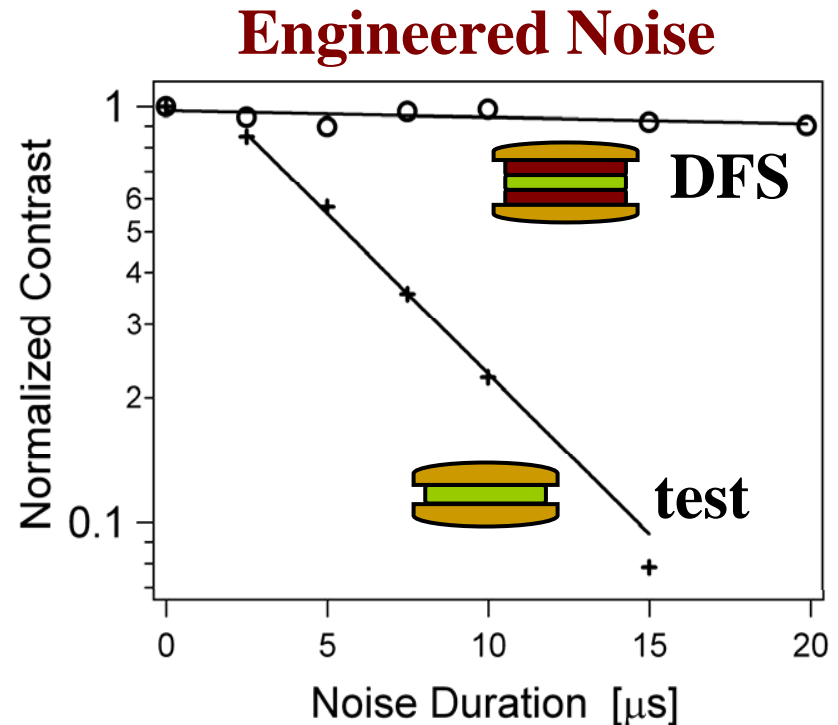
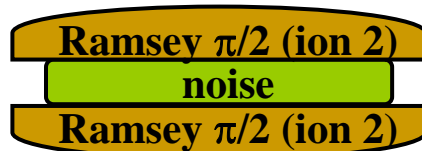
Entanglement for Decoherence Suppression

How is the Experiment Done?

- a) Encode an arbitrary qubit and apply noise



- b) Compare with noise applied to an arbitrary unencoded qubit



Also works with Ambient Noise



Error Correction for Ions

- After optimizing our pulse shapes and creating a DFS we need to examine the the ECC's
- Steane has shown a CSS [127,29,15] code for a 300 qubit quantum computing and 1Gop
 - 127 qubits, 29 logical qubits, $(15-1)/2=7$ errors
- Knill has a teleportation code that allows for errors of up to 10^{-2}
- The BS codes have some simplicity in operational complexity

Entropy removal: Error correction

- **Strategy: Post Selective QEC**

- Encode quantum information in 4 qubit error *detection* code + concatenation
- Teleport often. Every qubit is operated on at every time step.
- Post select on the outcome of Bell measurements. Operations and error correction are integrated into teleportation.

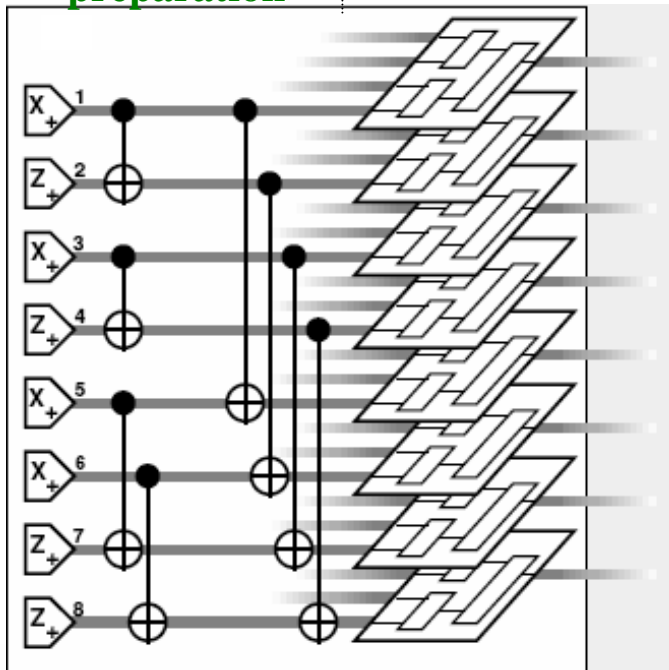
- **Resources:**

- High fidelity Bell pairs encoded in 8 qubits
- Use parallelism to purify the encoded Bell pairs

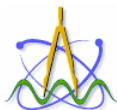
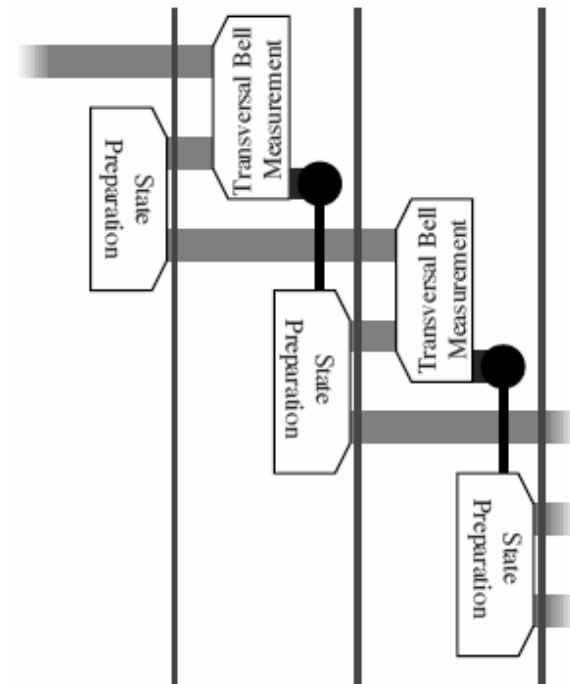
E. Knill, quant-ph/0312190,
quant-ph/0402171,
quant-ph/0404104

Bell state
preparation

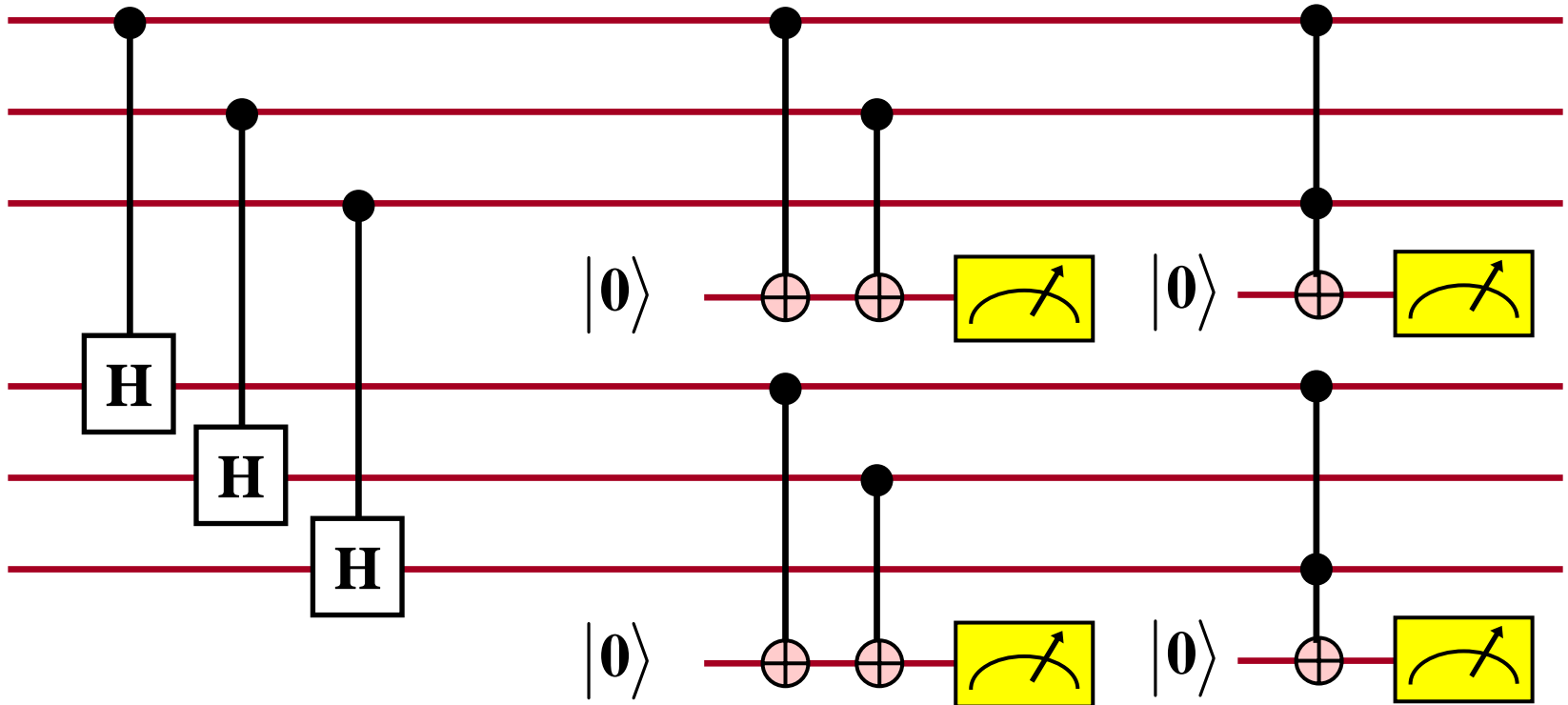
Purification



Information Flow



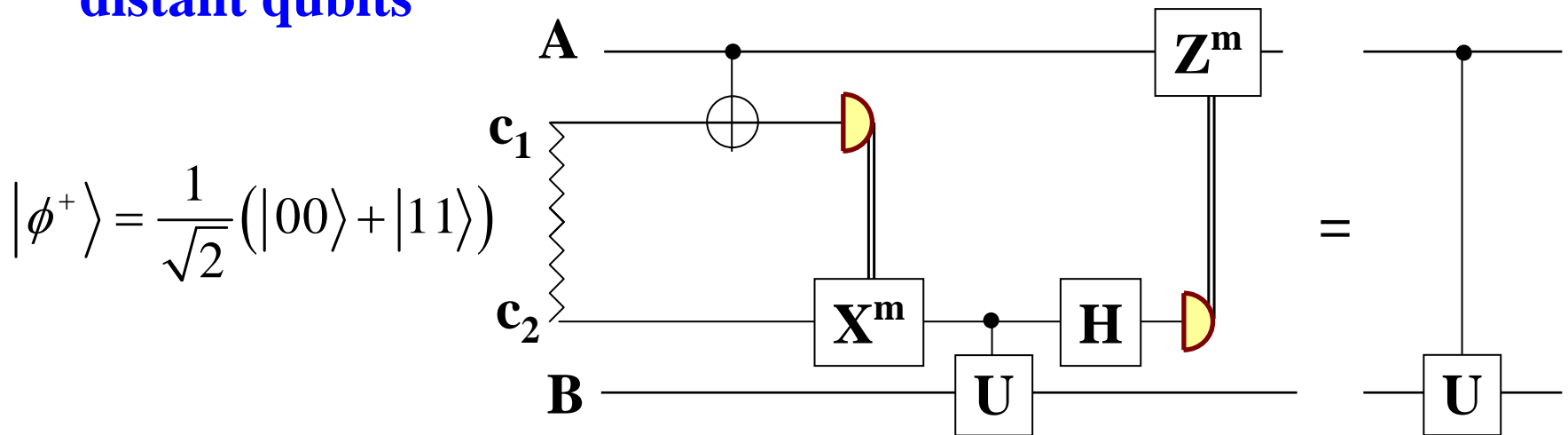
The Problem: View I



Statement of Problem: For fault tolerant QC it is necessary that one can interact arbitrary qubits and desirable to maximize parallelism of quantum gates!!!

Nonlocal Gates

Given prior entangled separated pair one can connect two distant qubits



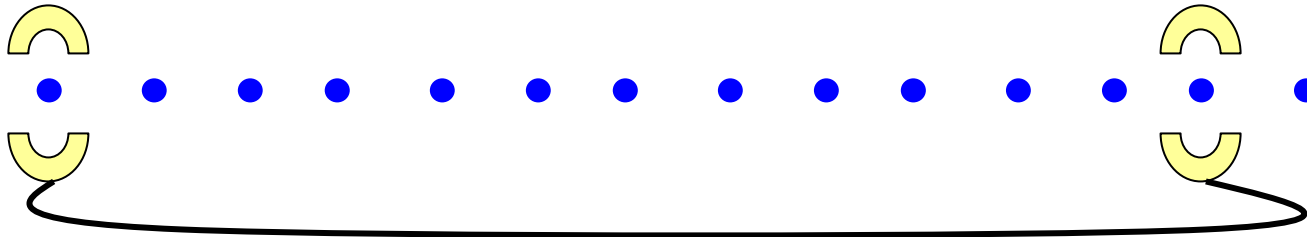
Need n EPR pairs for Controlled- $n(U)$ gate

D. Gottesman and I. L. Chuang, *Nature* 402, 390 (1999)

**J. Eisert, K. Jacobs, P. Papadopoulos and M. B. Plenio,
Phys. Rev. A 62, 052317 (2000)**

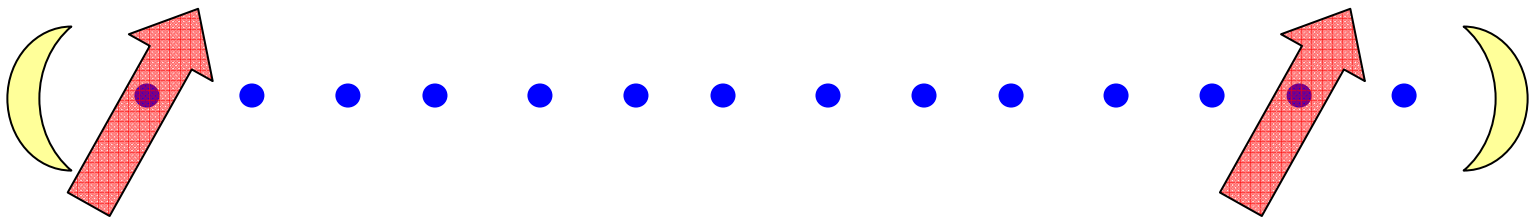
Inter-qubit communication

Flying Qubits



Requires efficient interconversion of material qubits and photons
Needs space for coupling cavities

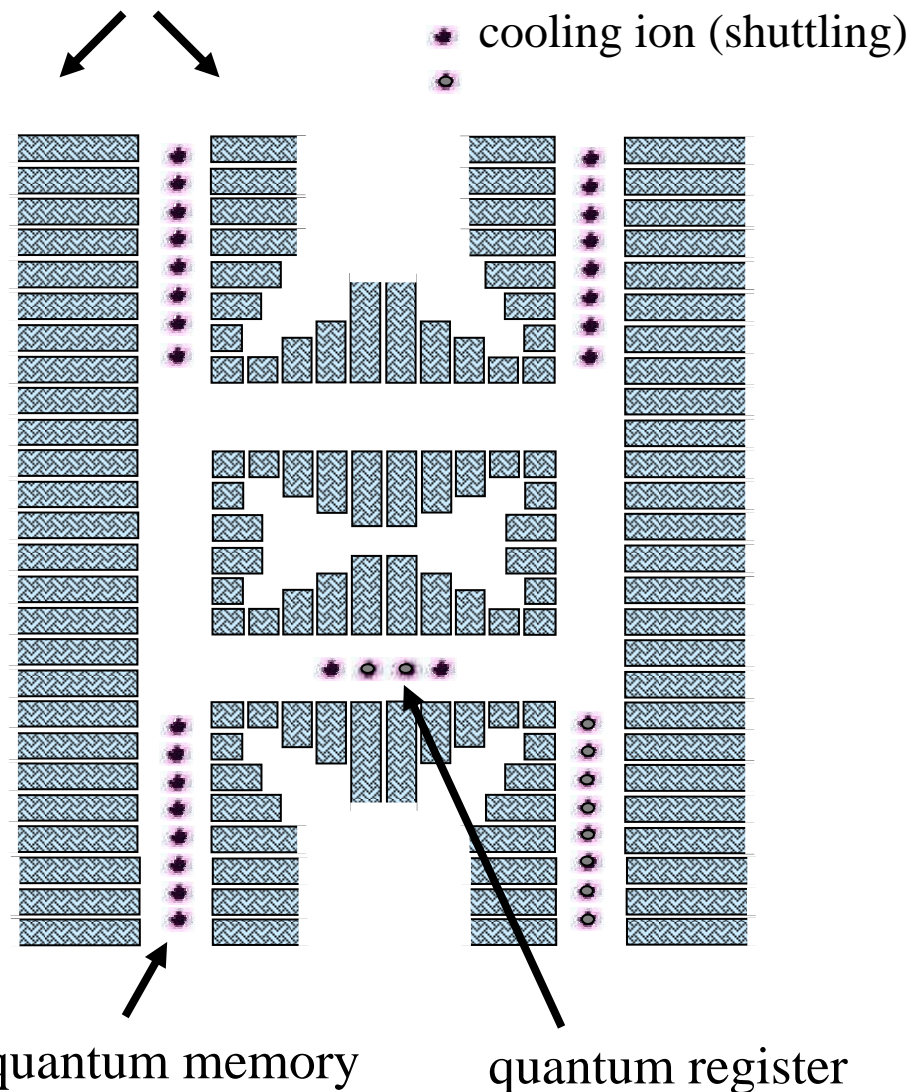
Common mode coupling (*e.g. vibrational mode of ion trap*)



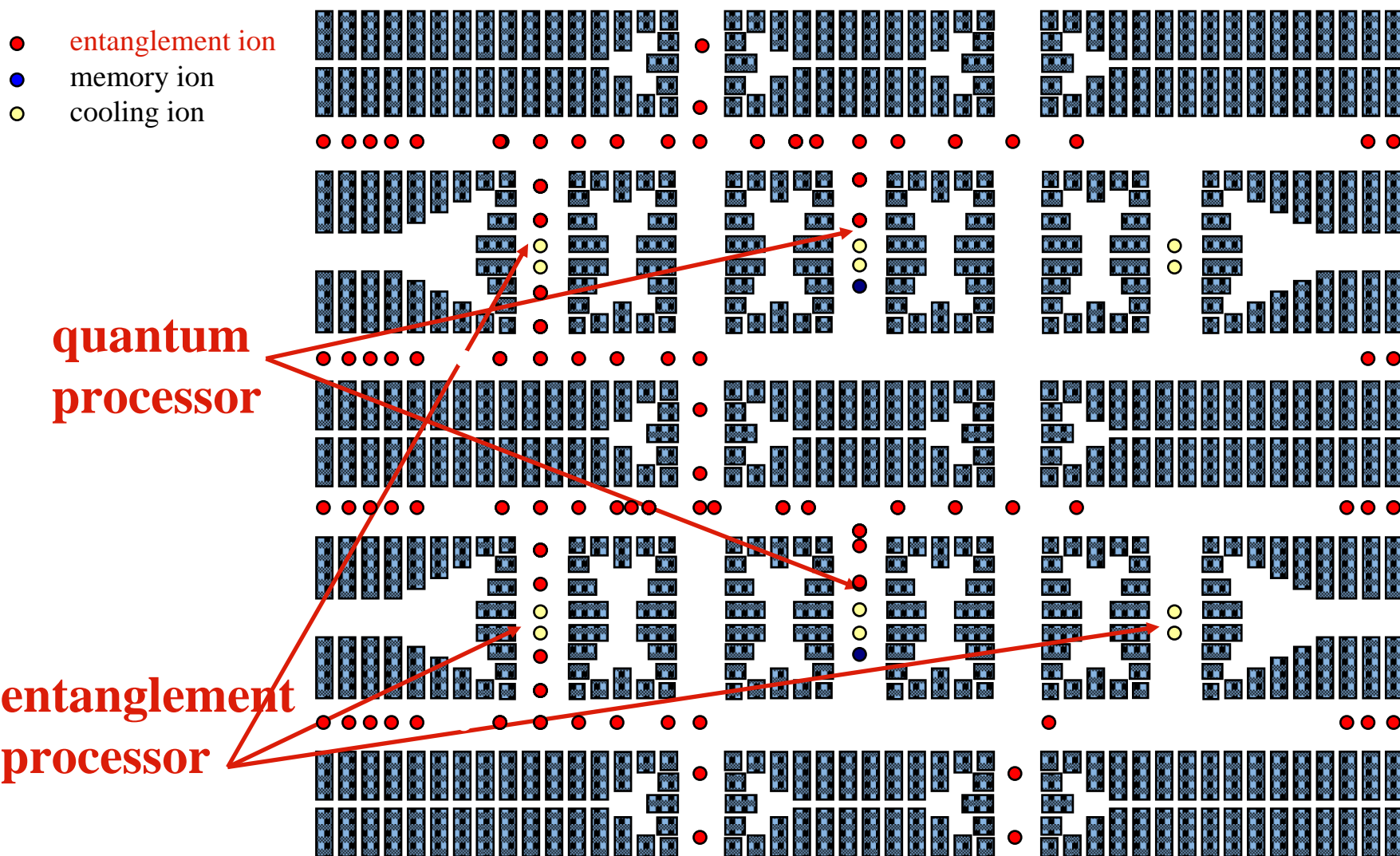
Interactions always on, opens a channel for decoherence
Cross talk problem – especially with many ions

Quantum CCD Architecture

Kielpinski, Monroe, & Wineland
Nature, June 13, 2002



Scalable Ion Processor





Benefits of Ion Approach

- **Atoms provided by Nature (all perfectly identical)**
- **Naturally decoherence-free**
 - (natural “environment” is free space)
- **Initialization Robust**
- **One-qubit operations well-established, high quality**
 - (e.g., atomic clocks)
- **Two-qubit gates now routine**
 - Numerous variations with and w/o addressing
- **High-efficiency quantum measurement (readout) well-established**
- **Movement of ions now routine**
 - Maintains entanglement
 - Separation of ion pairs routine

